Drilling Active Tectonics and Magmatism (Volcanics, Geoprisms, Fault Zones Post-SAFOD)

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Executive Summary

NSF Workshop Report: Drilling active tectonics and magmatism
(Volcanics, Geoprisms, and Fault Zones Post-SAFOD)

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A workshop was held in Park City, Utah, in May 2013, sponsored by the National Science Foundation. This workshop, attended by 41 investigators in active tectonics and geodynamics, explored how continental scientific drilling can be used to better understand active tectonic processes expressed by faults, earthquakes, volcanoes, and volcanic provinces. Emphasis was placed on the goal of helping to define a U.S.-based program of continental scientific drilling with an international scope. Participants were asked to define compelling scientific justifications for examining the active tectonics and magmatic processes related to faults and volcanoes that can be addressed by coordinated programs of continental scientific drilling and related site investigations. They were also asked to evaluate a wide range of proposed drilling projects, based on White Papers submitted by workshop participants and others. Our goal for this workshop was to provide a roadmap of specific science objectives and projects that address the most pressing current issues in active tectonics. The scientific questions and targets discussed here align with the priorities specified in the recent National Research Council report "New Research Opportunities in the Earth Sciences" (NRC, 2012), as well as previous NRC reports (NRC 2008, 2011).

Linkages with other Federal agencies (e.g., USGS, Department of Energy, Department of Defense), Integrated Ocean Drilling Program (IODP), International Continental Drilling Program (ICDP), and international partners were judged to be critical for a successful U.S. continental scientific drilling program. Program linkages allow resources to be leveraged across programs in order to maximize return on investment for all participants. Recent examples of intra-agency efforts include the Chesapeake Bay drilling project (USGS, ICDP), the Snake River Drilling project (DOE, ICDP, USAF), and the "PTA" drilling project on Mauna Kea (U.S. Army, NSF). Additional linkages should be sought with industries that rely on drilling (geothermal, hydrocarbon, and minerals exploration).

Participants working on faults and fault zone processes highlighted two overarching topics: (1) Understanding the seismic cycle and (2) 4-dimensional mechanics and architecture of fault zones. Major questions include:

- *How and why do earthquakes initiate? [White Papers by Carpenter, Savage]*
- *What physico-chemical mechanisms control earthquake triggering and interaction?*
- *What controls the spectrum and style of fault zone slip rates?*
- *Are there clear textural and mineralogical records that are diagnostic of the spectrum and style of fault zone slip rates?*
- *What are the controls on, and records of, the evolution over the seismic cycle of permeability, fluid pressure and flow, the stress field, strength, and temperature?*
- *How do faults act as barriers and conduits for fluids? How does this influence mineralization, heat flow and generation of fractures, and migration and storage of multi-phase fluids (H_2O, CO_2, CH_4, H_2, He and magma)*
- *How do the mantle, the lower crust, and upper crust interact? What are the avenues and rates of mass, heat and fluid transport?*
- *On tectonic timescales, how do geometry, composition, stress, processes, and mechanical properties of fault zones evolve?*

Five projects were recommended for consideration at this time, addressing one or several of these topics. Recommended projects range from inducing earthquakes to investigate earthquake initiation and triggering to investigation of detachment fault mechanics and fluid flow in a number of sites in the western USA, and the Rio Grande Rift.

Participants working on active volcanism identified six themes: the volcano eruption cycle; eruption sustainability, near-field stresses, and system recovery; eruption hazards; verification of geophysical models; and interactions with other Earth systems. Major questions include:

- *What controls the spatial and temporal evolution of magma migration, storage, and eruption style?*
- *What are the systematic and asystematic aspects of eruption cycles?*
- *How do eruption cycles integrate with ecological and local societal systems?*
- *How can we improve short- and long-term eruption forecasting?*
- *How reliable are models for internal processes and structures of volcanoes, as inferred from surface observations?*
- *What are the climate impacts of volcanic eruptions?*
- *To what extent can volcanic systems help us understand tectonic and geodynamic processes?*

Four projects were recommended for consideration at this time: Okmok volcano, Aso caldera, Mt. St. Helens, and Newberry volcano. These project could serve as an interdisciplinary natural laboratory to address several relevant problems which are transferrable to other volcanic systems, such as improved methods for identifying eruption history and constraining the rheological structure of shallow caldera regions.

Participants working on Geodynamics identified four major themes: Large Igneous Provinces (LIPs), Ocean islands, continental hotspot tracks and rifts, and convergent plate margins (subduction zones: Geoprisms). Major questions include:

- *Are LIPs, oceanic islands, and hotspot tracks the result of deep-seated thermal and chemical anomalies, or do they result from plate tectonic processes in the upper mantle?*
- *What is the nature of the melting anomalies that produces LIPs, Ocean islands, and hotspot tracks (thermal, chemical)?*
- *What are the scales of mantle heterogeneity and variation in partial melting for LIPs, oceanic volcanoes, and hotspot tracks?*
- *What are the magma production and lava accumulation rates for LIPs, oceanic volcanoes, and hotspot tracks? What are typical durations of volcanism?*
- *What are the environmental impacts of LIP volcanism? Is LIP emplacement responsible for mass extinctions, Oceanic Anoxic Events, etc.?*
- *How and in what proportion do melting, fractionation, or assimilation of crustal components control magma chemistry and where do these processes occur?*
- *Can we establish geochemical and isotopic links between a "plume head" volcanic province and its corresponding "plume tail" province?*
- *What causes the intrinsically high water and oxygen fugacities of arc magmas?*

Five projects were highlighted for consideration at this time: the Deccan traps LIP (with linkages to IODP for off-shore drilling), Snake River plume track drilling, two projects in Hawai'i (Mauna Kea and Mauna Loa), and a potential subduction zone (Geoprisms) project. In addition to these recommended projects, a number of other proposals were considered significant but less mature.

Broader Impacts: *This workshop brought together a diverse group of scientists with a broad range of scientific experience and interests. White papers submitted in advance of the workshop were circulated to all participants to foster discussion during the breakouts at the workshop, which were notable for the number of new contacts and collaborations made between people from different institutions and agencies. A particular strength of this workshop was the involvement of both early career faculty, who will be the ones to initiate and carry out the research programs that were defined, and more senior researchers with many years of experience in scientific drilling and active tectonics research. Future involvement of early career faculty and graduate students will have an enormous impact on their future research success, as well as on the success of the continental scientific drilling program. Young investigators brought new ideas to the table that will impact current and future projects. The preparation and education of the geoscience workforce has a high priority in industry and academia, and the implementation of strong scientific drilling projects will enhance these goals. A number of recommendations were made for technologic advancements, including robust instrumentation for down hole measurements and observatories, tools for orienting core, improved gas and fluid sampling tools, and advanced drilling and coring techniques. The group also recommended that procedures and protocols for sharing the large, multi-faceted datasets inherent to drilling operations be developed through the NSF Earthcube program and initiatives such as EarthChem and IGSN. Each of the themes and questions outlined above has direct benefits to society including improving hazard assessment, direct monitoring of active systems for early warning, renewable and non-renewable resource and energy exploitation, and predicting the environmental impacts of natural hazards. The workshop participants emphasized that these transformative scientific questions are best addressed through scientific drilling, which provides unique opportunities for probing active systems. The results from this workshop are being disseminated to the broader community in presentations to ICDP, reports in EOS and Scientific Drilling. The workshop report and white papers can be found online at* http://digitalcommons.usu.edu/geology_facpub/386/.

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I. INTRODUCTION

Forces originating deep within the active Earth are expressed on Earth's surface, where they have a profound effect on human societies. On a global scale, these effects include the development of mountain ranges and subduction zones. On a local scale, they are expressed as active faults (with slip ranging from a few meters to hundreds of kilometers) and volcanoes (ranging from individual volcanoes to large volcanic chains or fields).

The significance of these tectonic processes for human societies is well known, from the cataclysmic eruption of the super-volcano Santorini in 1650 BCE, to more recent plate boundary earthquakes and tsunamis in Indonesia and Japan, and the strike-slip earthquake in Haiti that killed hundreds of thousands of people. Even less massive events can have a profound effect on local populations. Active faults and volcanoes are common in the western United States, but recent destructive earthquakes in Virginia and Oklahoma, along with the compilation of active faults in the US (USGS, 2012) show that few parts of the country are immune. Further, much of the world's population live near fault zones or volcanoes.

Understanding how fault systems and volcanoes operate is crucial to mitigating these hazards. Unfortunately, studying young active systems is difficult because earthquake nucleation and propagation, as well as crucial magmatic processes, take place hundreds to thousands of meters below the surface, obscured from direct or simple observation techniques. Although deeper parts of faults and volcanic plumbing systems may be exposed by erosion in older terranes, information on active processes can only be inferred. In young active terranes, critical relationships are still hidden beneath the Earth, and require deep scientific drilling to be studied.

The Workshop

In order establish how continental scientific drilling can be used to address these critical societal issues, a workshop was held in Park City, Utah, in May 2013, sponsored by the National Science Foundation, and attended by 41 investigators in active tectonics and geodynamics. This workshop explored how continental scientific drilling can be used to better understand active tectonic processes expressed by faults, volcanoes, and volcanic provinces. Although emphasis was placed on our goal of helping to define a U.S-based program of continental scientific drilling, participants included representatives from Canada, Japan, India, Italy, Great Britain, and New Zealand, who are actively engaged in international research efforts in cooperation with U.S.-based investigators. A list of participants with their affiliations is found in Table 1, and a list of presentations from the meeting is in Table 2.

Workshop Goals

Participants were asked to define significant scientific justifications for examining the active tectonics and magmatic processes related to faults and volcanoes that can be addressed by a coordinated program of continental scientific drilling and related site investigations. Workshop participants were also asked to prioritize these processes, and to propose the types of faults and volcanoes that would be targeted by these efforts. Our goal for this workshop was to provide a roadmap of specific science objectives and projects that address the most pressing issues in active tectonics drilling.

In addition to exploring the scientific issues that drive a need for continental scientific drilling, potential projects were discussed and evaluated within the context of these drivers. Workshop participants addressed the scientific motivations for these proposed projects and their corresponding target sites, and attempted to prioritize them based on the strength of the science drivers, and on their readiness for formal review. Many of these proposed efforts are interdisciplinary and are directly related to on-going NSF initiatives (e.g., Geoprisms; IRIS; Earthscope), and apply to a range of scales, from localized fault systems to plate boundary faults, and from small monogenetic vents to super-volcanoes. Other projects are being supported in part by other agencies, e.g., USGS and Department of Energy, or internationally (e.g., drilling in the Deccan traps). The members of this workshop team examined these issues in detail and the product is a roadmap of specific projects to address the most pressing issues in drilling active fault and volcanic systems.

Workshop Organization

Workshop participants were asked to provide, prior to the meeting, White Papers on specific drilling targets, more generalized focus areas, or on techniques that can be applied to a range of projects. These White Papers were distributed digitally to all participants before the workshop, and White Paper authors were allowed to update and revise their White Papers after the workshop in order to reflect what they learned during the meeting. These White Papers are an Appendix to this report: (http://digitalcommons.usu.edu/geology_facpub/386/).

The workshop spanned two full days of meetings. On Day one, keynote speakers presented talks on "Trends and Topics" in scientific drilling of faults and volcanoes (see Table 1). This was followed in the afternoon and on the morning of Day Two by short talks (5-10 minutes) by the workshop participants highlighting their White Papers; a complete list of these presentations is in Appendix B. The remainder of Day Two was devoted to breakout groups on faults, fault processes, active volcanism, and the geodynamics of volcanic terranes. At the end of Day Two, scribes from each breakout group presented summaries of their findings. Finally, the Steering Committee met on Day Three to prepare a draft report.

Building on Past Success

The concept of using deep continental drilling to address long-standing problems in active tectonics is not new, and some of continental drilling's most successful projects have grown out of issues related to active processes in faults and volcanoes, and those related to chemical geodynamics of the Earth. The success of these projects demonstrates the effectiveness of continental scientific drilling, and these projects formed the basis for the new projects proposed and discussed at this workshop.

Drilling projects that have addressed the mechanics of fault zone processes include SAFOD (Zoback et al., 2010), the Chelungpu fault (Taiwan) Drilling project (Ma et al 2006), the Alpine (New Zealand) fault project (Towend et al 2009), the Nojima fault drilling project, the Wenchuan, China project (Ma et al., 2006), and (within the oceanic realm) the NanTroSeize plate boundary project to drill faults within an accretionary prism (Tobin et al 2006, 2009).

Drilling projects that addressed the origin, evolution, or eruptive mechanisms of volcanoes or young active volcanic terranes include the Mt. Unzen scientific drilling project (Nakada et al. 2005) and the Iceland Deep Drilling Project (IDDP: Friöthleifsson and Elders, 2005; Elders and Friöthleifsson, 2009). Projects focusing on chemical geodynamics include the Hawai'I Scientific Drilling Project (DePaolo et al 1996, 2007; Stolper et al 2009) and Hotspot: the Snake River Drilling Project (Shervais, et al., 2006, 2012).

II. THE BROADER CONTEXT

Continental Scientific Drilling is not an end in itself; it is a tool for studying processes that cannot be accessed through normal surface-based investigations. As such, it complements existing NSF programs such as *GeoPrisms*, *Earthscope*, *Frontiers in Earth System Dynamics (FESD)*, *Integrated Earth Systems (IES)*, *Critical Zone Observatories (CZO)*, *Petrology and Geochemistry*, *Tectonics*, and *Paleo Perspectives on Climate Change (P2C2)*. Scientific drilling is also an important component of other agency programs, such as the *U.S. Geological Survey (USGS)*, the *Department of Energy* (DOE: geothermal energy, CO_2 sequestration) and the *Department of Defense* (DOD: geothermal energy). As a result, the science drivers for *Continental Scientific Drilling* overlap with the science objectives in these programs.

Science Drivers for USA Continental Drilling

The goals addressed by participants at this workshop reflect priorities for Earth science research that have been proposed to NSF in a series of recent NRC reports (NRC 2008, 2011, 2012). For example, in regards to faults and fault zone mechanics, the 2012 NRC report "New Research Opportunities in the Earth Sciences" recommends *"EAR should pursue integrated interdisciplinary quantification of the spectrum of fault slip behavior and its relation to fluxes of sediments, fluids, and volatiles in the fault zone. The successful approach of fault zone and subduction zone observatories should be sustained, because these provide an integrative geosystems framework for understanding faulting and associated deformation processes."*

Similar observations and goals are proposed for volcanic systems and mantle geodynamics: *"Volcanoes and their associated hydrothermal systems provide the primary means by which the mantle passes material to the oceans, atmosphere, and crust. Volcanoes probably created Earth's early atmosphere and oceans, and they continue to resupply these regions with water, CO_2, and other constituents that keep Earth's surface habitable"* (NRC, 2008), and *"Evidence of this small-scale convection is provided by hot spots—large clusters of volcanoes, the most active of which are in Hawaii, Iceland, the Galapagos Islands, Yellowstone, and Reunion (Indian Ocean). Hot spots are usually explained as the surface outpourings of magma formed in mantle plumes, which are cylindrical upwellings of hot (and hence low viscosity) rock that are thought to form near the base of the mantle and rise to the surface at rates much faster than plate velocities. Mantle plumes should form as a consequence of heat entering the bottom of the mantle from the much hotter outer core"* (NRC, 2008).

Continental scientific drilling is viewed as an important tool for attaining these goals. Drilling provides access to samples and situations that are not attainable by other means, and is central to the installation of observatories at depth in fault zones and volcanic terranes.

Integration with other drilling programs

It is important to remember that Continental Scientific Drilling funded by NSF does not exist in a vacuum: there are other programs and agencies that support CSD projects both domestically and internationally. Domestic agencies that fund drilling science include the Department of Energy, the Department of Defense, and the U.S. Geological Survey. International programs include the International Ocean Drilling Program, the International Continental Drilling Program, and the domestic funding agencies of many foreign governments. As noted in the most recent NRC report: *"EAR can enhance the impact of its research portfolio by encouraging and supporting interagency and international coordination of facilities, community consortia, and individual investigations."* (NRC NROES, 2012).

Many of these programs have goals and objectives that coincide with those fostered by NSF, or which complement NSF's programs. In some cases, these agencies will fund drilling projects that address science objectives similar to those supported by NSF (e.g. IODP, ICDP, USGS). In others, these agencies may fund drilling project that have more practical objectives, but which have collateral benefits for pure science investigations (e.g., DOE, DOD). In both cases, support of PI's by NSF can be crucial for U.S. investigators to take advantage of these opportunities.

Learning from IODP: Continental Drilling can be improved by adapting the approaches and procedures developed by IODP to CSD projects. These include database implementations, logging and sampling protocols, initial reports, and follow-up studies. These have proven to be extremely efficient in disseminating data and advertising the availability of samples and data for follow-up studies. Adapting these to CSD will be important for bringing new people and communities to the program.

Workshop participants strongly endorsed the following viewpoints:

- Funding from other Agencies (*e.g.*, DOE, DOD, USGS) and International Partners (*e.g.*, ICDP, IODP) can be critical for many drilling projects, and may comprise the main or only funding for some projects. These projects represent significant opportunities for U.S. scientists by removing the need for NSF support of drilling operations, resulting in what the workshop participants referred to as "free core".
- There is a strong need for NSF support for science investigations to leverage these resources, even though the drilling was not paid for by NSF. Funding U.S.-based scientists to work on samples (or on down hole studies) obtained by non-NSF funded drilling projects will allow NSF to focus more of its resources on science investigations, and significantly lowers the demand for logistical support (drilling). These opportunities fall into two broad groups:

- *Science support for US-based investigators in international collaborations*. Many international projects (supported by ICDP and foreign agencies) welcome the participation of U.S. PI's, but participation is contingent on support of those PI's by NSF. In many cases only science-related funding is needed; in others, some logistical or drilling support is also required (but much less than the full cost).

  An example related to this workshop is the Koyna Drilling Project in India, which is funded by ICDP and the Indian government to core several sections through the Deccan traps; the Indian research focus is on reservoir-induced seismicity, but there is a significant opportunity to carry out petrologic and geochemical studies on the core (see White Paper by Kale, this volume).

- *Science Support for U.S.-based investigators with non-NSF drilling support*. Domestic U.S. agencies that support scientific drilling, such as DOE, DOD, and the USGS, often have a more programmatic approach to drilling projects, with goals that complement but do not match NSF science objectives. These agencies may not provide funding to address science objectives that do not align with their programmatic goals. Nonetheless, the core samples produced (or the hole itself) may present major opportunities to address NSF-supported science objectives.

  An example related to this workshop is the Snake River Geothermal Drilling project, funded by DOE and DOD, which has produced ~5.3 km of core; agency funded science focuses on physical properties of the core and hydrology. There is a major opportunity here for petrologic and geochemical studies as well. Another example is the "PTA" drilling project on Mauna Kea, funded by the U.S. Army (white paper by Garcia).

- There needs to be better integration between the U.S. *Continental Scientific Drilling* program and IODP. While there is a range of existing projects in fault-zone processes that already address this (*e.g.*, J-FAST, NantroSEIZE, Alpine Fault-DFDP, proposed Hikurangi margin drilling), there is little coordination between IODP and continental drilling projects that address active magmatism or geodynamics. For example, workshop participants see opportunities to study hotspot-related continental breakup with onshore studies of continental LIPS and off-shore studies of the resulting plume track (see below).

III. FAULT ZONE PROCESSES AND GEOMECHANICS

Workshop participants interested in active faulting recognized that the key scientific questions and hypotheses proposed in the white papers submitted to the workshop, and most topical among this research community at present could be summarized in two major topics and associated set of subquestions: *Topic 1: Understanding the seismic cycle and Topic 2: 4D mechanics and architecture of fault zones.* These concepts are expanded in below. We also identify white papers (Appendix 1) that provide further detail of each of the sub-questions.

Topic 1: Understanding the seismic cycle

1. How and why do earthquakes initiate? *[White Papers by Carpenter, Savage]*
2. What physico-chemical mechanisms control earthquake triggering and interaction? *[White papers by Carpenter, Omura, Savage, Singh]*
3. What controls the spectrum and style of fault zone slip rates? *[White papers by Carpenter, Hadizadeh, Reinen & Toy, Lee]*
4. Are there clear textural and mineralogical records that are diagnostic of the spectrum and style of fault zone slip rates? *[White papers by Carpenter, Hadizadeh, Reinen & Toy, Schleicher]*
5. What are the controls on, and records of, the evolution over the seismic cycle of permeability, fluid pressure and flow, the stress field, strength, and temperature? *[White papers by Carpenter, Christie-Blick, Kale, Kampman, Omura, Savage, Fulton, Lee]*

Topic 2: 4 dimensional mechanics and architecture of fault zones

1. How do faults act as barriers and conduits for fluids? How does this influence mineralization, heat flow and generation of fractures, and migration and storage of multi-phase fluids (H_2O, CO_2, CH_4, H_2, He and magma) *[White papers by Ball, Kampman]*
2. How do the mantle, the lower crust, and upper crust interact? What are the avenues and rates of mass, heat and fluid transport? *[White papers by Ball, Kampman, Martel, Miller & Lee]*
3. On tectonic timescales, how do geometry, composition, stress, processes, and mechanical properties of fault zones evolve? *[White papers by Ball, Christie-Blick, Hadizadeh, Martel, Miller & Lee]*

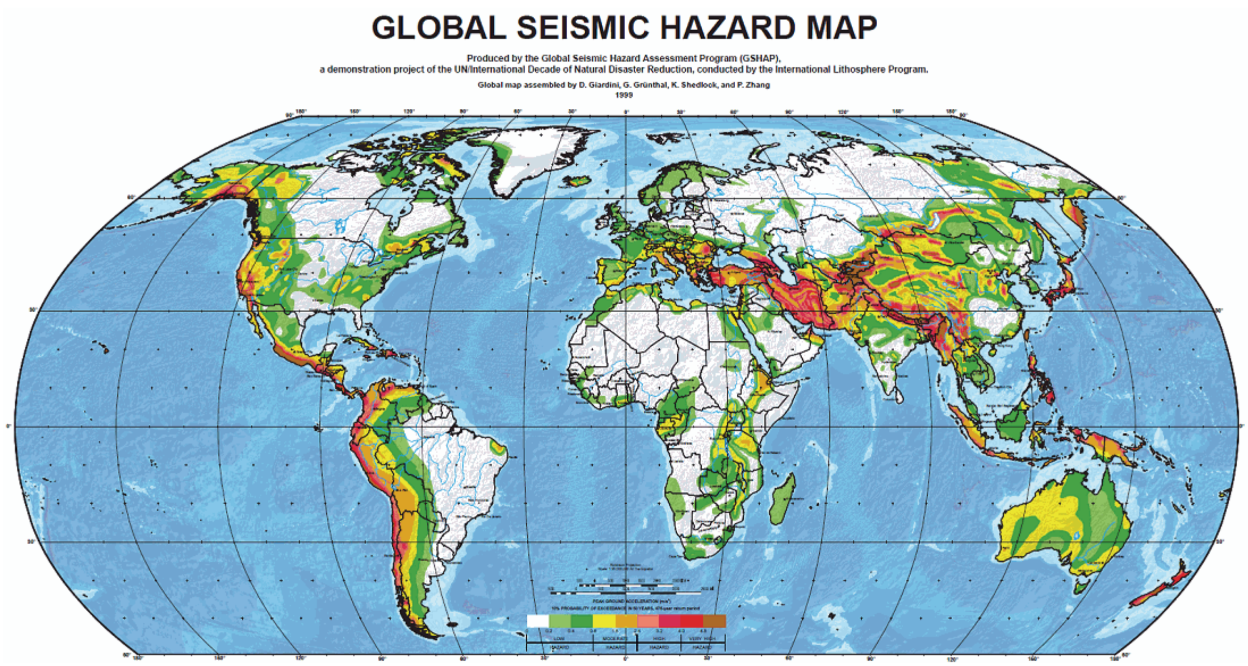
Why is scientific drilling necessary to study faults and fault zones?

Scientific drilling provides unique access to dynamic geologic environments and samples. As a scientific community, we are interested in examining active processes at in situ conditions (P, T, fluid conditions) at depth before they are overprinted or altered during exhumation. The following advantages to drilling active tectonic targets were emphasized by the workshop participants:

- Drilling allows us to explore the full range of conditions and scales observed at depth in nature, which cannot be replicated in the laboratory.
- Installation of observatories in the subsurface allows measuring the environmental conditions at depth over timescales comparable to the seismic cycle (e.g. coseismic, afterslip or aftershock sequence durations).
- By drilling we can collect in situ samples of rocks, fluids, gasses, microbes from depth and over time.
- By drilling we can measure in situ geophysical, geochemical, mechanical, physical and hydrological conditions and their evolution over time.
- In particular, borehole techniques provide the only conventional methods for measuring stress.
- Borehole seismometer installations dramatically increase the signal:noise ratio and accuracy of our seismic records.
- By drilling we can obtain fairly continuous records of how fault and host rocks and physical conditions vary in three dimensions around fault zones. These records expand incomplete surficial records.
- Understanding active magmatic interactions in the deeper crust is only possible through drilling.
- We may be able to sample rock that is actively deforming at conditions not found in the near surface (e.g. those with a temperature-dependent rheology).
- Drilling into active tectonic or magmatic environments stimulates new technology development and testing.

Specific Projects/Sites Recommended By The Workshop

The active faulting group prioritized several future drilling projects that will address the key topics outlined in the scientific questions section above. The first two of these fall into the 'Understanding the seismic cycle' topic and the last three are closely aligned with the '4D mechanics and architecture of fault zones' topic. However, we emphasize that there are significant potential overlaps between all of the projects outlined below.



Global Seismic Hazard Map, produced by Global Seismic Hazard Assessment Program (GSHAP), of the International Lithosphere Program. D. Giardini, G Grünthal, K. Shedlock, and P. Zhang.

A. Understanding the seismic cycle

1. Reoccupying and extending the SAFOD site [white paper by Carpenter et al.]

This project proposes to drill an additional multi-lateral borehole off the existing SAFOD main hole, to penetrate a repeating earthquake patch (the Hawaii, HI, patch). There has already been significant investment in the San Andreas Fault Observatory at Depth (SAFOD). Established infrastructure includes two boreholes and downhole instruments. Microstructure and physical properties of fault rocks from the active fault zone, fluids and gases, and physical conditions at depth have already been characterized and there is an extensive suite of geophysical data, including high resolution seismological records. New observations from recovered material, downhole measurements and monitoring can be directly compared to the results of these previous studies.

2. Triggering earthquakes for science [white paper by Savage et al.]

The physical mechanisms driving earthquake nucleation, propagation and arrest, and the triggering of earthquakes by both distant earthquakes and anthropogenic perturbations to the subsurface are unknown. This project proposes to design and install an observatory consisting of terrestrial and borehole seismometers and down-hole strain and pore pressure sensors to make in-situ measurements of the stresses and strains at the source of nucleation. An earthquake occurring within the observatory is critical to the success of the project. The probability of capturing a natural earthquake in the exact fault patch that has been drilled is miniscule. To overcome this problem, the project will draw on the recent advances in unconventional energy extraction and trigger an earthquake within the observatory by pumping water into the fault at depth.

B. 4-dimensional mechanics and architecture of fault zones

3. Mechanics of the Sevier detachment [white paper by Christie-Blick et al.]

The Sevier Desert detachment initiated at, and accommodated normal slip of <47 km, at a dip of ~11°, as recently as the Holocene (< 8 ka), implying it has very low effective frictional strength. Drilling aims to elucidate the mechanism(s) or physical conditions that result in such weakness, and more broadly to characterize fault zone geometry. Magneto-telluric studies demonstrate fluids interact with the structure at depth so this project also addresses fault-fluid interactions. An ICDP workshop has already been held to define both scientific objectives and a preliminary drilling plan, and the workshop group considers that pursuing the project further will address the aims of Topic 2.

4. Tectonic evolution and mechanics of the Rio Grande rift [white paper by Ball et al.]

The Sangre de Cristo fault system accommodated late Quaternary extension in the northern Rio Grande rift. However, surficial geology and a wealth of geophysical data show the structure is complex and has a long tectonic history. Scientific drilling through multiple and representative elements of the SCF presents opportunities to better understand the processes of fault system evolution within an intracontinental rift and provide an analog to other extensional terranes. In-situ fault zone characterization, rock sample collection, hydraulic and thermal experimentation, and in-situ stress determination would provide the subsurface ground truth and monitoring necessary to evaluate hypotheses on tectonic evolution, modern strain accommodation, and the heterogeneity created by faults. Significantly, this project will develop results that address seismic hazard and groundwater resource exploitation in the wider Rio Grande rift region.

5. Fluid flow and supercritical fluid-rock interactions in the Little Grand Wash fault [white paper by Kampman et al.]

Carbon dioxide degassing normal faults at Green River, Utah are important analogues to engineered geological CO_2 storage. Surface studies have provided important constraints on the CO_2 source and the Quaternary degassing history of the faults, which imply large temporal variations in fault hydraulic behavior. Recent drilling at the site provided core and fluid samples that constrain fluid flow and fluid-rock reaction in the shallow subsurface (~300 m). Deep drilling at depths >800 m, where the CO_2 is supercritical, presents an opportunity to investigate how these mantle-derived volatiles react both within a fault damage zone and with the surrounding reservoir rocks and impermeable seals. Instrumental observations of in-situ stress, fracture permeability and fluid flux, combined with acoustic measurements of two-phase flow and geochronological studies of carbonate mineralization would provide invaluable information on fault damage zone fracture flow and the relative importance of tectonic, climatic and geochemical controls on fault hydraulic behavior.

C. Active Tectonics: Other Potential Targets

The following target sites and project ideas were also agreed to have significant scientific merit by the workshop participants. However, these proposals were considered less mature than those discussed above, and will require more development before they can be considered for funding.

- ***Dixie Valley [White Paper by Wannamaker]:*** An active Basin & Range fault with hydrothermal/magmatic interactions; possibly also induced seismicity. The fault is already being drilled by DOE, and it makes sense to take advantage of this campaign. However, we assign slightly lower priority to this site because the same scientific questions are able to be addressed through drilling at the Rio Grande Rift.
- ***The Snake Range Detachment fault zone [White Paper by Miller and Lee]*** provides the opportunity to investigate the coupling between brittle and ductile crust; in particular we can consider if the footwall was rigid or experienced a form of channel flow/stretching. A major question is "how do the thermal structure of crust and/or rates of extension control the formation and evolution of this and similar faults?".
- ***Mono Basin [White Paper by Jayko et al]:*** Drilling the tectonically and volcanically active Mono Basin to measure the stress field and evaluate the role of the Eastern Sierran frontal fault system on controlling the timing, location and rates of magmatism and volcanism. These issues are crucial for defining the tectonics of the Walker Lane, assessing the role of faults as conduits for magmatism and for evaluating the geothermal energy potential in the area.

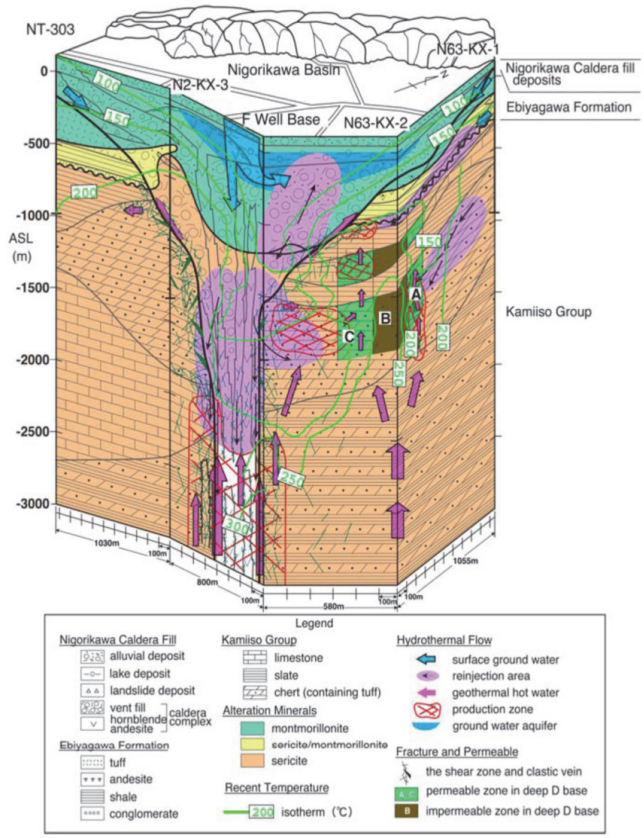
- ***The San Andreas fault near Little Rock:*** It is proposed the asymmetric damage zone characterized from surface outcrops, was generated co-seismically, perhaps due to preferential rupture propagation direction or because of differences in mechanical properties of the wall rocks. Drilling to quantify the spatial distribution of fault damage in the subsurface could validate whether the surficial structure was indeed generated coseismically at depth by coring across the fault zone.
- ***The San Andreas fault at San Juan Bautista [White Paper by Hadizadeh et al.]:*** Geodetic records clearly document that this site, at the northern end of the creeping section of the San Andreas Fault, accommodated some slip during a 'slow earthquake' at ~2-4 km depth in 1998. Drilling and coring the rupture area of the slow earthquake could access fault rocks and conditions surrounding faults that accommodated slip at the full spectrum of rates (from slow creep to earthquake rates).
- ***The Puysegur Subduction Zone [White Paper by Reinen and Toy]:*** The young (<11 Ma) incoming Australian Plate crust at this seismically active (e.g. it accommodated an Mw 7.9 event in 2011) subduction zone has morphology indicating it may have peridotite at or very near the surface. Thus it is possible the subduction thrust interface is within ultramafic rock or serpentine. The latter mineral has peculiar mechanical properties that mean it may slip seismically, or creep aseismically depending on the imposed slip rate (e.g. Reinen et al., 1994; Reinen 2000). The subduction zone is fairly well-instrumented so slip distribution models can be constructed, there are a diverse range of ground shaking proxies on land in the Fiordland area (e.g. landslide records), and the area is subject to a proposal to collect a large transect of geophysical data under the GeoPrisms initiative. This site therefore represents a good future opportunity to investigate how serpentine in particular plays a role in slip rate behavior of faults.

IV. ACTIVE MAGMATIC SYSTEMS

Active volcanic systems are important both to science and society – hazards to human populations associated with volcanic eruptions are significant in many parts of the world and have in the past resulted in tens to hundreds of thousands of deaths.

Understanding the life cycle of typical volcanic systems is crucial to managing the risk associated with their eruptions (Eichelberger and Uto 2007). Of particular interest is the nature and distribution of volatiles, both juvenile and meteoric, which drive most explosive volcanic eruptions and are the primary risk factors in post-eruptive hazards such as lahars and the mass failure of hydrothermally altered volcanic edifices (sector collapse). Understanding these risk factors is critical to the prediction and monitoring of hazardous eruptions.

Active magmatic systems also drive hydrothermal circulation, which has been linked to exhalative and epithermal mineral deposits (e.g., Au, Ag, Cu, Mo, Pb, Zn), and to high-enthalpy geothermal energy resources (Elders and Sass 1988; Fournier 1999; Eichelberger and Uto, 2007). These linkages provide the opportunity for multi-disciplinary studies that combine hazards analysis with both green energy and mineral resource research. Such linkages are critical to obtaining funding from a range of sources, thereby spreading the both the risk and cost associated with drilling across several agencies or interest groups.



Schematic diagram of Nigorikawa Caldera, where both the geothermal system and the structure of a young volcanic vent have been revealed through commercial geothermal drilling (from Eichelberger and Uto, 2007, after Hanano 2005).

Active volcanoes also provide information about mantle and crustal chemistry and dynamics. All active volcanoes carry information about their source regions and the processes that drive melting in their setting. Depending upon the location (i.e., oceanic or continental crust) magma composition will yield information on the source region and/or contamination processes, as well as crystallization kinetics and sequences. Examples include Hawaiian volcanoes, which provide information on deep-seated mantle processes and geochemical fractionation within the Earth, and arc volcanoes, which are driven by complex processes that include decompression melting, fluid flux from the subducting slab, and partial melting of subducted sediments and altered basalts. There are also practical questions, e.g., are associated mineral deposits generated by the composition of the source region or through post-magma generation contamination? These issues have strong societal relevance and demonstrate the importance investigating through drilling active magmatic systems.

"Volcanic eruptions provide spectacular and frequent (more than 70 different volcanoes erupt every year) reminders that Earth is a dynamic and evolving planet. Lava flows, pyroclastic flows, and ash fall are proximal hazards; gases and dust lofted into the atmosphere have global effects on climate, life, and air traffic. Volcanic hazard does not end with the eruption—lahars and landslides create hazards long after an eruption ends. Despite a long history of investigation, numerical models of volcanic processes, laboratory characterization of the properties of magmas, and real-time monitoring of active volcanoes are only now beginning to show their promise to both predict eruptions and quantitatively interpret volcanic deposits" (NRC NROES, 2012).

Scientific and Technical Rationale for Drilling Active Magmatic Systems

Active magmatic systems (volcanoes) are extremely challenging environments for drilling. They are characterized by high temperatures, corrosive gasses and fluids, and wide variations in physical rock properties. None the less, they are also extremely rewarding when drilling is successful. The motivations for scientific drilling into active volcanic systems include:

(a) sampling of deep uncontaminated materials (rocks and fluids and gases), (b) sampling hydrothermal systems, hydrothermal alteration, (c) quenched magmas, temperature gradients-heat flow, (d) state of stress and strain related to magma systems, (e) geometry of magma and hydrothermal plumbing systems, (f) physical properties in zones of active deformation and seismicity associated with magma intrusion, and (g) time dependence of temperatures, stress, strain, fluids, volatiles; these may require installation of observatories to monitor over time.

Scientific questions in active magmatic systems

Outstanding questions related to active magmatic systems revolve around the fundamental issues of understanding how volcanoes work and constraining what hazards they may pose in the future. The detailed questions and problems that fall under these headings can be summarized in five main categories below:

- Volcano eruption cycle: What is the spatial and temporal evolution of magma migration and storage? What is the temporal evolution of eruption style? What are the systematic and asystematic aspects of eruption cycles?
- Sustainability, stress, and recovery. How do eruption cycles integrate with ecological and local societal systems? (interdisciplinary – stress and recovery following eruptions for Bio and Eco systems).
- Eruption hazards. How can we improve short- and long-term eruption prediction? To what extent can we forecast near-field (e.g., lava flows, pyroclastic flows) and regional to global hazards (e.g., ash plumes)? (interdisciplinary beyond Geo. Societal impacts)
- Verification of Geophysical Models: How reliable are estimates and uncertainties for internal processes and structures of volcanoes, determined from surface observations? (seismic tomography, reflection, and anisotropy; gravity; magma plumbing systems –geometry and strength; stress/thermal regimes –also time dependence)
- Interactions with other Earth systems. What are the potential climate impacts of volcanic eruptions? To what extent can volcanic systems help us understand tectonic and geodynamic processes?

One critical way to constrain the hazards posed by a particular volcano is to document its eruptive history. Drilling and extracting core can contribute to this goal by probing a volcano's deep geologic history that is not accessible from surface outcrop. Such drilling can help to 1) quantify magmatic flux through time, 2) characterize temporal evolution of eruption style through time, including documenting detailed eruptive stratigraphy in order to identify precursory eruptive patterns, and 3) document the temporal evolution of erupted magma composition (magmatic chemistry and volatile content). These temporal sequences also contribute to answering geodynamic questions related to using volcanic products to understand the evolution of the chemistry and dynamics of melt source regions and magma migration pathways as they relate to tectonic conditions.

Another way to reduce volcanic hazards is real-time monitoring. *Borehole instrument packages* have proven to be successful (e.g., at the Soufrière Hills Volcano, Montserrat) because of their very high sensitivity to changes deep in the volcanic system. Monitoring packages should measure (1) state of local stress and strain, which may provide eruption warning by detecting subsurface magma migration, (2) seismic data which may also provide clues about rock fracture and fluid migration, (3) temperature, and (4) pore pressure.

Drilling also can serve to constrain geophysical properties of the edifice. Geophysical imaging and interpretation of geodetic data hinge on several critical physical parameters, and improved constraints of these parameters will serve to improve both monitoring and development of conceptual models of the subsurface plumbing system. Syn-drilling measurements should include resistivity, moduli (in situ & laboratory measurements), material strength, thermal conductivity, country rock porosity and permeability, seismic velocities, and rock density.

A more ambitious investigation of active magmatic systems involves drilling the magmatic plumbing system at depth (e.g., Unzen drilling project: Nakada et al. 2005). The motivations behind drilling magma at depth include characterization of the plumbing system geometry (e.g., conduit or dike width, lateral and vertical variations in magma properties within a dike or conduit), testing models of magma chamber structure and melt distribution (what is the structure of a magma chamber?), analysis of detailed chemistry, mineralogy of chamber boundary zone (what does the transition from hydrothemal circulation to melt zones look like?), constraining the moduli/strength of chamber boundary zone, and obtaining quenched samples at depth to better-constrain original magamatic volatile abundances.

Specific Projects/Sites Recommended By The Workshop

Workshop participant discussed a wide range of proposed scientific drilling projects in all areas of Active Magmatic Systems. Discussions focused primarily on projects presented in the attached White Papers and by workshop participants. Some of these project proposals were deemed to be mature enough to proceed through the formal proposal process. Others proposals were judged to need more development before moving forward as formal proposals. The following assessment discusses both mature proposals and those deemed worthy of consideration but which require more development to move forward. More details on all of these projects can be found in the attached White Papers. Although certainly not an exhaustive list, several sites have been suggested as possibly fruitful drilling targets. Each of these sites is represented by at least one White Paper in the Appendix. Several of these represent mature proposals for which much of the preliminary site survey work is either in progress or has already been largely completed. See section V for projects involving active Hawaiian volcanoes.

1. **Okmok Volcano, Alaska, USA** *[White Paper by Masterlink et al]*

Okmok Volcano has produced two caldera-forming eruptions in last 10,000 years, along with frequent smaller eruptions. Okmok could serve as an interdisciplinary natural laboratory to address several relevant problems which are transferrable to other volcanic systems. These include improving methods for identifying eruption history (timing, magnitude, and style) and constraining the rheological structure of shallow caldera regions and the influence on magma migration and storage. Key goals of the drilling project would include identifying eruptive materials comprising the shallow caldera, determining the rheologic structure of the shallow caldera, verifying seismic tomography and magma migration models and quantifying related uncertainties, and characterizing, in space and time, stress and thermal regimes associated with the subsurface plumbing system.

Okmok project components and activities include pre-drilling geophysical surveys (geodetic, seismic, gravity, EM) to refine hypotheses and preliminary numerical models. Syn-drilling activities would obtain materials, thermal, and geophysical measurements to a few kilometers (magma? → bonus!). Post-drilling activities fall into three main categories: laboratory analyses and experiments (petrology, geochemistry, rheology), borehole geophysics (thermal, fluid characteristics, stress and strain), and numerical modeling in order to verify seismic tomography and magma migration patterns, and characterize loading/stress and thermal regimes (in space and time). The broader context of studying Okmok volcano includes Integration of the USGS with NSF and other initiatives and interests:

- Knowledge gained is potentially transferable to any actively deforming system (volcanoes and fault systems alike). This has huge implications for geophysical data initiatives, e.g., Earthscope and remote sensing missions such as NASA DESDynI, Japan ALOS, ESA Sentinel, $100M+ missions.

- Goals dovetail nicely with those of other scientific programs and agencies, including several cross-disciplinary programs, e.g., the Aleutians Science Corridor of Geoprisms, and the USGS Volcano Hazards program, which combines geophysics and geoinformatics. Okmok is an existing USGS research target, with a focus on volcano hazards for Aleutians and societal impacts (such as the North America-Asia air corridor). There is the potential to develop applications for other active volcanoes, and the Okmok project could be a catalyst for new interdisciplinary initiatives (for example, field/Lab/Space-borne data + numerical methods = STEM showcase).

- DOE/Geothermal Energy industry: Dike propagation results from pressure-induced hydrofracturing, which can be used to model enhanced geothermal systems (EGS), which are a major focus of the DOE Geothermal Programs office.

2. ***Aso Caldera, Japan*** *[white paper by Nakada]*

Aso Caldera is a large caldera, which may be overdue for eruption. The scientific goals of drilling Aso Caldera include gaining a better understanding of:

- Structural evolution of the last caldera eruption (ring-fault zone)
- Temporal and spatial relationships of caldera-collapse and climactic eruptions
- Precursory phenomena of climactic eruption events
- Environmental impact of eruptions on life and recovery
- Most effective monitoring and subsequent prediction techniques for its hazardous volcanic events

3. ***Mount St. Helens, Washington, USA***

Mt. St. Helens is a natural target because it erupts frequently and has the potential to affect large populations in the continental US, especially if ash-fall is significant. The Mount St. Helens system is well-characterized because it has been and continues to be extensively monitored. Furthermore, there is an upcoming Geoprisms-sponsored geophysical imaging project, paving the way for all the preliminary work required to support an ambitious drilling project.

4. ***Newberry Volcanic Monument, Oregon, USA*** *[White Paper by Frone]*

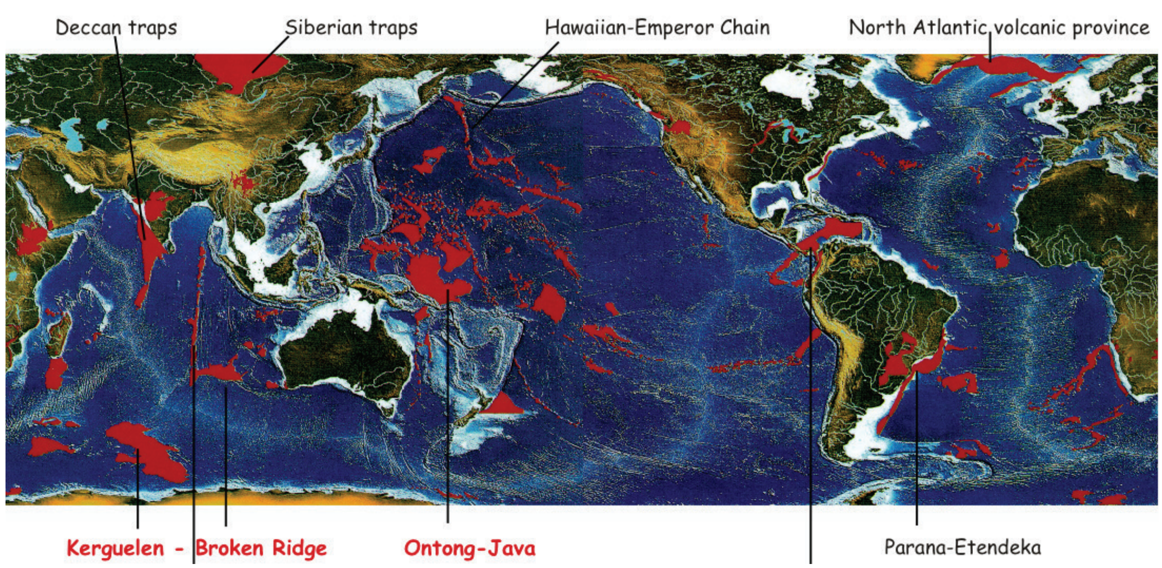
Newberry Volcano is one of the largest Quaternary Volcanoes in the conterminous US; it covers ~1600 km^2 and has a volume of ~450 km^3 (MacLeod & Sherrod, 1988). It has experienced at least two caldera forming eruptions (~300 ka and 83±5 ka), and has had several other recent eruptions, including the 7 ka (post-Mazama) sequence of dominantly basaltic andesite, and Intra-caldera rhyolites, the youngest of which is 1.3 ka. Its magmatic system is apparently bi-modal, resides in the backarc and could put a large population at risk (ranked very dangerous by the USGS). Scientists are particularly interested in the depth, volume (estimated to be 1 – 8 km3), composition, and melt fraction of the proposed magma chamber at 3 – 6 km depth. Significant geophysical data has been collected to support drilling efforts at Newberry, including lidar, gravity, magnetotellurics, areomagnetics, and seismic tomography. In addition, at least two holes have been drilled already (to 932 m and 424 m depth), from which useful data may be extracted without additional drilling operations.

V. GEODYNAMIC AND GEOCHEMICAL EVOLUTION OF EARTH

The geodynamic and geochemical evolution of the Earth are intimately linked to two dominant processes of heat transfer: plate tectonics (driven by the sinking of cold lithospheric plates in subduction zones, and the rise of hot asthenospheric mantle below midocean ridges to form oceanic crust) and the rise of thermally (and possibly compositionally) buoyant mantle to form hotspots with their associated ocean island basalts and flood basalts. Together these dominant processes are responsible for the Wilson cycle, in which continents continually grow by collision and amalgamation with other continents, rupture to form new continental fragments, and then collide again. Continents also grow over time through the addition of new continental crust formed in island arcs by the subduction of oceanic crust.

Plumes and Large Igneous Provinces (LIPS)

The connection between deep-seated mantle plumes, ocean island basalts, and large igneous provinces (LIPS) is becoming relatively robust as new techniques in mantle tomography establish visible connections between hotspot volcanoes and deep thermal anomalies (DePaolo and Weiss 2007). What does the time-integrated development of LIPS tell us about mantle reservoirs involved in their formation? Are any of these reservoirs located in the deep mantle, or at the core-mantle boundary? Do these reservoirs change over time, or with location? How do deep-seated magmatic sources affect crustal architecture and evolution? LIPS may also have significant implications for short-term climate change that can affect biotic evolution and extinctions, and some may be tied to Ocean Anoxic Events (*Tejada et al*, *2009; Erba et al*, *2010*).



Large Igneous Provinces, from Mahoney, J.J. and M.F. Coffin (eds.), Large Igneous Provinces: Continental, oceanic, and planetary flood volcanism. AGU Geophys. Mon. 100: 438 p., 1997

"Determining the magnitude, spatial distribution, and temporal variability of geochemical heterogeneities and pinpointing the locations of internal reservoirs where they are sequestered are key to understanding how the deep interior contributes to Earth's evolution" (NRC, 2012).

Research into Plumes and LIPs can be divided into three focus areas that can be addressed by Continental Scientific Drilling and also in collaboration with ocean drilling:

1) Large Igneous Provinces exposed on land, largely continental flood basalts but also including emergent portions of oceanic LIPs. The current paradigm suggests that these represent catastrophic melting of an engorged "plume-head" at relatively shallow depths, but other non-plume models have also been proposed;
2) Ocean island chains that are thought to represent the active conduits of deep-seated mantle plumes erupted through oceanic lithosphere as it moves continuously over the relatively fixed thermal anomaly;
3) Continental hot-spot tracks, which are thought to represent the intra-continental equivalent of ocean island chains, form as continental lithosphere moves continuously over the relatively fixed thermal anomaly. As with LIPs, non-plume models have also been proposed for both ocean island chains and continental hot-spot tracks.

Each of these focus areas engages a series of significant scientific questions that overlap in part, but also address some distinct issues. For example, continental flood basalts erupt huge volumes over geologically short time spans, which may have significant environmental impacts. However, because they erupt through continental crust, their compositions are effected to various extents by interactions by subcontinental mantle lithosphere or continental crust. In contrast, oceanic plateaus (oceanic flood basalts) and ocean island chains erupt over prolonged time spans, but are erupt through thin oceanic lithosphere, which has only minimal impact on their chemical and isotopic composition. Continental hotspot tracks erupt magmas that may be strongly affected by continental interaction, such that their chemical and isotopic compositions may be decoupled. Therefore, drilling in the ocean basins (on ocean islands) will recover material free from contamination by continental crust.

Scientific Issues addressed by CSD on Large Igneous Provinces include:

- What are the mode(s) of eruption during flood basalt formation?
- What is the duration of LIP volcanism?
- How does the LIP source vary over time?
- What is the mode of LIP origin - – is it through deep-seated plumes or from the upper mantle only, or can it be a combination of both?
- What are the environmental impacts of LIP volcanism – Is LIP emplacement responsible for mass extinctions, Oceanic Anoxic Events, etc.?
- What is the nature of the melting anomaly that produces LIPs (thermal, chemical)?
- How does the flood basalt magma source evolve over time?
- Does one model fit all LIPs?

Scientific Issues addressed by CSD on Ocean Island chains include:

- What is the scale of mantle heterogeneity and variation in partial melting for oceanic volcanoes?
- What are the magma production and lava accumulation rates for oceanic volcanoes and do these rates vary over time?
- How do oceanic island volcanoes grow (internal vs. external growth)?
- What is the heat flow within an oceanic volcano?
- Are there significant gaps in the volcanic section during the volcanoes magmatic history?

Scientific Issues addressed by CSD on Continental Hotspot Tracks

- How do the variations in magma chemistry, isotopic composition, and age of eruption constrain the mantle dynamics of hotspot-continental lithosphere interaction?
- What do variations in magma chemistry and isotopic composition tell us about processes in the crust and mantle? To what extent is magma chemistry controlled by melting, fractionation, or assimilation of crustal components, and where do these processes occur?
- Is the source region predominately lithosphere, asthenosphere, or plume? What are the proportions of each? Are there changes in the magma source/proportions at any one location along the plume track through time relative to the position of the hotspot?
- How does a heterogeneous lithosphere affect plume-derived mafic magma? Effect of crust-lithosphere age, structure, composition, and thickness on basalt and rhyolite chemistry, from variations in lava chemistry along the plume track.
- What is the time-integrated flux of magma of continental plume-track volcanic system? Is it consistent with models of plume-derived volcanism, or is this flux more consistent with other, non-plume models of formation?

- Can we establish geochemical and isotopic links between the "plume head" volcanic province, and the "plume tail" province?

Workshop participants also endorsed the concept of integrated onshore-offshore studies that combine CSD projects on continental LIPS with IODP or Special Platform studies of ocean islands related to that LIP.

LIPS, and the Continental Flood Basalt-LIP connection: Integration with IODP

The close genetic relationship among continental flood basalts (CFBs), LIPs, and ocean island chains presents a unique opportunity for linkages between continental scientific drilling (CSD) and the *Integrated Ocean Drilling Program* (IODP) and its successor, the *International Ocean Discovery Program*. These linkages were highlighted at an NSF-IODP workshop held in Colraine, Northern Ireland, in 2007 (*Neal et al, 2008*). They include onshore-offshore linkages between CFB's and their related "plume-tail" oceanic tracks, and the onset of continental rifting, syn-LIP sedimentation (which preserves the onset of LIP eruptions). A key target for ICDP drilling should be the sill complexes presumed to underlie most LIPs. These complexes, relatively inaccessible in ocean basins, are important for four reasons: (1) they are an important element in the magmatic plumbing of each LIP, (2) volatile-release at sill-sediment contacts contributes greatly to climate impact, (3) valuable deposits of Ni, Cu, and Pt-group elements are located in these sills, and (4) intrusions in sedimentary basins influence the maturation of petroleum deposits and complicate exploration for such deposits. An understanding of the sill complexes, therefore, has important economic implications, in both continental and oceanic settings.

> *"Reconciling geochemical evidence favoring isolated mantle reservoirs, seismic evidence for down-welling slab material in the lower mantle, and geodynamic models that tend to favor extensive, although possibly intermittent, circulation remains at the heart of this long-standing controversy. With rapid growth of human population, society faces increasing exposure to catastrophic effects of earthquake faulting, tsunamis, and volcanic eruptions."* (NRC NROES, 2012).

Subduction Systems and Geoprisms

The large-scale evolution of subduction zones and volcanic arcs is fundamental to understanding how continental crust form. What magmatic processes create intermediate magmas? What roles do lateral accretion and magmatic intrusion play in the growth of arc crust? Is the lower mafic crust of the arc recycled back into the mantle and, if it is, how is this accomplished? How much of the magma at a convergent margin is new juvenile addition to the crust and how much is recycled older crust? What causes the intrinsically high water and oxygen fugacities of arc magmas? These large-scale questions have not been addressed by continental drilling but some have been addressed by ocean drilling projects that sample the non-emergent parts of these systems. But there are many questions about how arcs form and evolve that can only be addressed by drilling projects that look at the long-term life cycle of magmatic arcs whose older roots are buried by younger activity.

"Concerted community efforts to study subduction zones such as GeoPRISMs bring together diverse research communities that can address the volatile budget and flux problem, and large-scale studies of uppermantle structure such as those conducted under the Continental Dynamics and EarthScope programs now regularly cast interpretations of seismic models in terms of coupled thermal, volatile, and chemical heterogeneities rather than solely thermal models" (NRC NROES, 2012)

Most drilling activity related to subduction systems, or to Geoprisms, will be carried out by IODP, because for the most part active subduction systems are found below sea level. However, these are portions of some active systems, as well as many fossil systems, that are found on land; these areas are the subject of the ExTerra initiative of Geoprisms. The ExTerra initiative seeks to understand subduction dynamics by investigating exposed portions of active systems or a few well-preserved fossil systems.

For example, drilling an exposed supra-subduction zone mantle wedge can provide continuous core thru this system, which would be impossible to obtain from an active fore-arc. Further, drilling projects can be combined with surface mapping and geophysics to build a detailed 3D model of mantle wedge architecture. Rock properties can be studied *in situ* at the outcrop scale or larger, providing more realistic constrains than lab experiments on hand samples (for example, vertical seismic profiles, or cross-hole experiments between two or more drill holes). Finally, if core can be oriented relative to earths magnetic field, intrinsic properties such as rock magnetism and lattice preferred orientation fabrics can be measured and compared to experimental results and observed subduction systems.

Specific Projects/Sites Recommended By The Workshop

Workshop participant discussed a wide range of proposed scientific drilling projects in all areas of geodynamics. Discussions focused primarily on projects presented in the attached White Papers and by workshop participants. Some of these project proposals were deemed to be mature enough to proceed through the formal proposal process. Others proposals were judged to need more development before moving forward as formal proposals. The following assessment discusses both mature proposals and those deemed worthy of consideration but which require more development to move forward. More details on all of these projects can be found in the attached White Papers.

Geodynamic and Geochemical evolution of Earth: Potential targets

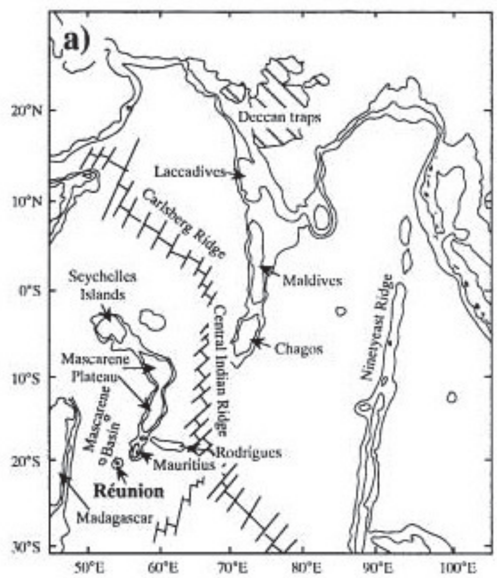
LIPS, and the Continental Flood Basalt-LIP connection: Integration with IODP

One of the most significant and poorly-understood geologic processes is the movement of deep-seated mantle material, possibly from the core-mantle boundary, to the base of the lithosphere, where it melts adiabatically to form massive volcanic provinces. Continental flood basalts, LIPs, and ocean island chains are all related to this process, and any attempt to understand this process requires progress in all three settings.

Several high-priority projects were identified by the workshop participants, representing all three areas of interest. These include projects that are currently being drilled, and holes that were recently drilled, with non-NSF funding (ICDP, DOD, DOE, and international partners). Also included are new projects that will require funds for drilling as well as science and curation.

1. ***Deccan Traps, India: US Participation in the Indian Koyna Drilling Project and Joint ICDP-IODP Drilling of the Deccan-Reunion Hotspot track*** *[White papers by Kale, Neal]*

At the Park City workshop an update was given with regard to the Indian initiative to drill through the Deccan Traps flood basalt pile. The discussion that followed showed that there is a unique opportunity to build upon this unique drilling target with further continental and ocean drilling. Plume theory posits that once the magmatism initiated by the surfacing plume head is exhausted there is a transition to plume tail magmatism that is lower in magnitude and compositionally distinct (e.g., Hill, 1991). The continental drilling conducted on the Deccan Traps has currently drilled through the lava pile and into the underlying Precambrian gneiss. Therefore, the first large Deccan Traps lava flow has been sampled and there are plans to drill two more holes through the lava pile in different locations.



Sketch map of the Indian Ocean showing relationship of the Deccan traps to hotspot islands and the Indian Ocean Ridge.

As can be seen from the figure, the Reunion Island-Deccan Traps trace extends southward from the western edge of the Deccan Traps, is bifurcated by the Central Indian Ridge, and terminates at Reunion Island. By combining continental drilling on the western edge of the Deccan Traps with that offshore along the hotspot trace, the plume hypothesis would be tested by evaluating the timing and extent of the change from plume head to plume tail magmatism, as well as investigating the heterogeneity of the two magma systems.

2. ***Snake River Plain Continental Plume Track***
[White Papers by Christiansen, Shervais, Hanan, Potter, Schmitt and Lee]

The Snake River volcanic province represents *the* world-class example of time-transgressive intra-continental plume volcanism. The SRP is unique because it is young and relatively undisturbed tectonically, and because it contains a complete record of volcanic activity associated with passage of the hotspot which can only be sampled by drilling. The central questions addressed by drilling the SRP are: (1) how do mantle hotspots interact with continental lithosphere, and (2) how does this interaction affect the geochemical evolution of mantle-derived magmas and continental lithosphere? At this time, three new deep drill holes have been completed, with funding from the International Continental Drilling Program, the Department of Energy, and the Department of Defense. Further scientific work on the 5.5 km of core produced by this project will require funding from NSF. This project represents a prime example of the opportunities presented by intra-agency cooperation and joint support of projects, especially those where all of the drilling costs are borne by other agencies.

3. Other Potential LIP-Flood Basalt Targets

Participants identified additional potential targets for scientific drilling of LIPS and flood basalts, along with their related hotspot tracks. These include:

a. Etendeka-Walvis Ridge: This is a Plume Head – Plume Tail couplet in the South Atlantic ocean that formed coincident with the opening of the South Atlantic.
b. CAMP: On-shore and Off-shore: The Central Atlantic Magmatic Province (CAMP) formed during the early opening of the central Atlantic – the first segment of the Atlantic ocean to form, and a type locality for a "volcanic rifted margin." CAMP magmatism began with the intrusion of Triassic dikes and sills, and continued with volcanic eruptions into the Jurassic.
c. Ethiopian Traps: The Ethiopian traps represent the onset of LIP volcanism in a continental setting. They form our best modern example of LIP volcanism, and can be related to rift zone volcanism to the south, and ocean basin formation to the north.

Ocean Islands: The Oceanic Record of Plume Tail Volcanism

In order to evaluate geochemical and isotopic components in the mantle geodynamic framework, it is necessary to avoid contamination from continental crust – which has extreme compositional and isotopic compositions that can mask more subtle mantle signatures. This is traditionally approached by sampling "plume tail" hotspot tracks that formed on oceanic crust. Because the oceanic crust is thin and compositionally similar to plume-derived basalts, this minimizes contamination and allows detailed evaluation of the mantle component. Ocean island drilling builds on the success of the Hawai'I Scientific Drilling Project (HSDP), and has tie-ins to LIPs and continental flood basalts. Two projects are highlighted here (Mauna Kea and Mauna Loa), and two other locations were found promising: Reunion (with its tie-in to Deccan drilling), and Kerguelan, a major oceanic plateau in the southern Indian ocean.

1. ***Mauna Kea PTA Project*** *[White paper by Garcia]*

Mantle plumes, such as the one that formed the Hawaiian Islands, have strongly influenced our views of Earth's deep mantle. Lavas from these areas are the principal geochemical probes into the mantle, and testing grounds for understanding Earth's mantle convection, plate tectonics, volcanism, and changing magnetic field (Stolper et al., 2009). Study of the petrology and geochemistry of oceanic volcanoes has contributed immensely to our present understanding of Earth processes (e.g., Weis et al., 2011). Drilling is essential to evaluation the temporal evolution and structure of mantle plumes because surface exposures typically reveal only a small fraction of a volcano's stratigraphy (e.g., ~3% of the 10- to 15-km height of Hawaiian volcanoes).

An unprecedented opportunity is available to gain a more detailed record of a Hawaiian volcano. The U.S. Army has funded (~$6 M) the drilling of two, ~2,000 m deep boreholes in search for water on the upper flank of Mauna Kea Volcano on the Island of Hawaii (PTA project). The first hole, located ~10 km from the volcano's summit, was completed to ~1760 m deep with a high rate of recovery (>90%). Operations are scheduled to start the second hole before the end of 2013. These two holes provide a rare prospect for detailed examination of the volcanic history of a Hawaiian volcano and will allow many important issues to be examined including:

- What are the magma production and lava accumulation rates for Hawaiian volcanoes? Lava accumulation rate estimates based on dating HSDP2 core are minimum values because of the location of the drill site 50 km from the volcano's summit and the problems encountered in dating the core, which was mostly deposited submarine sea level where rapid quenching and secondary minerals are common. The PTA section will be entirely subaerial. Thus, the lavas will be easier to date using Ar-Ar methods allowing us to better constrain magma production rates.

- What is the scale of heterogeneity and variation in partial melting within the Hawaiian plume? The PTA site location allows finer resolution of the volcano's geochemical variation and assessment of the structure of the Hawaiian mantle plume than the HSDP2 core. Work on historical lavas of Kilauea volcano has shown fine-scale source variations that are cyclic on scales of decades to centuries (Greene et al., 2013).
- What is the nature of the transition from shield to post-shield volcanism? The PTA core will provide an exceptional record of the timing and duration this transition as the volcano moves off the hotspot causing lower degrees of melting and change in source components (e.g., Hanano et al., 2012).
- How do Hawaiian and other volcanoes grow (internal vs. external growth)? Francis et al. (1993) proposed 2/3 of the growth of Hawaiian shield volcanoes is by endogenous (intrusive) growth. A new gravity study (Flinders et al., 2013) suggested that intrusions represent <30% of the mass of Hawaiian volcanoes. The close proximity of the drill site to the volcano's summit will allow us to evaluate this new interpretation.
- What is the heat flow within an oceanic volcano? Unlike the HSDP sites, the PTA site should not be affected by circulation of cold seawater. Thus, its temperature profile will be more representative of the heat flow above the Hawaiian mantle plume, which is poorly known.
- What is the extent of explosive volcanism for Hawaiian volcanoes? Kilauea's Holocene deposits record numerous major violent events and suggest its explosive frequency is on par with Mt. St. Helens (Swanson et al., 2011). Adjacent Mauna Loa is thought to have had a large explosion associated with a major debris avalanche (Lipman, 1980). Careful examination of the fragmental material in the core will provide insight into the frequency of explosive eruptions for this, and the other, major shield volcanoes on Hawaii Island, which will have implications for hazard mitigation and planning.

There is much we still do not know about how Hawaiian and other volcanoes grow, which has natural hazards implications. The new Mauna Kea Volcano drilling provides an exceptional opportunity to gain a detailed understanding of crustal and mantle processes within plume-related and other volcanoes at no cost to NSF for drilling.

2. ***Mauna Loa Project*** *[White paper by Rhodes]*

The most important recent result of Hawaiian studies is the resurrection of the concept of an asymmetrical mantle plume in which volcanoes along two en-echelon trends, the Loa and Kea trends, exhibit distinct major element and isotopic compositions [Abouchami et al., 2005; Weis et al., 2011]. This asymmetry in plume source components is attributed to asymmetry in the lowermost mantle preserved in the melting zone within the plume [Weis et al., 2011; Farnetani et al., 2012]. Loa trend magmas are thought to contain a greater contribution of re-cycled crustal material than those of Kea trend volcanoes. An unresolved and contentious problem is whether Loa magmas result from melting discrete lithological domains (pyroxenite/eclogite) of this crustal material within the plume, or whether they reflect melting of peridotite fertilized by pyroxenite/eclogite melts [Jackson et al., 2012]. In order to understand Hawaiian volcano growth, melt production and the identity, composition and lithology of plume components it is necessary to drill a Loa-trend volcano to obtain comparable information to that obtained by the HSDP for Mauna Kea, a Kea trend volcano [Stolper et al., 2009].

Mauna Loa, the world's largest active volcano (~100,000 km3], is the obvious candidate because a great deal more is known of its recent sub-aerial history (< 120 ka) and also of its earlier (> 400 ka) submarine growth than other Loa trend volcanoes [Rhodes, accepted for publication]. Consequently, more informed questions and problems can be raised and solved through drilling. These include:-

- Submarine lavas are significantly older [Jicha et al., 2012] than predicted by Hawaiian volcano growth models [Depaolo and Stolper, 1996; DePaolo et al., 2001]. Clearly, Hawaiian volcano growth models need revisiting.
- Current Mauna Loa sampling is bi-modal (sub-aerial < 120 ka; submarine > 400 ka). What was happening on Mauna Loa in the intervening 300 ka? Has shield-stage volcanism waxed and waned?
- Was the decline in eruption rates on the submarine southwest rift zone around 300 - 400 ka [Jicha et al., 2012] volcano-wide, or did eruptive activity shift to other parts of the edifice?
- Is there evidence for cyclical periods of explosive and effusive activity on Mauna Loa, as recently documented for Kilauea [Swanson, 2011]?
- Drilling on Mauna Loa's western flank could intersect the disconformity between lavas erupted before and after the giant Kona landslide, providing a possible opportunity to date this prodigious event.

Subduction Systems, Geoprisms: Potential targets

1. Drilling the Josephine Ophiolite –Direct Observation of a Subduction Zone Mantle Wedge
[Shervais and Dick white paper].

The question of geochemical flux in the mantle wedge during subduction is critical to our understanding of arc volcanism, and forms an important aspect of the global geochemical flux. These processes may be observed indirectly in active subduction systems by measuring inputs and outputs but this approach does not permit direct observation of dynamic processes within the mantle wedge source of arc magmas. Direct observation of mantle wedge peridotites is possible, however, by studying outcrops of mantle peridotite that underlie supra-subduction zone (SSZ) ophiolites. The Josephine ophiolite preserves the largest exposed tract of mantle peridotite in North America, and represents the fore-arc of a paleo-Cascadia subduction zone. It is one of the best places in the world to study chemical flux, structure, and subduction zone processes in a sub-arc mantle wedge. Microstructures and macrostructures that document deformation processes the mantle wedge are also well preserved, along with alteration and mineralization that document low to intermediate temperature metamorphism within the mantle wedge. Major questions we will pose include the cumulative extent of melt extraction and the nature of the melt extracted, the nature and extent of mantle-melt interactions subsequent to melt extraction (e.g., addition of melt from deeper in the asthenosphere), and the nature, source, and extent of fluid flux to SSZ peridotites.

VI. TECHNOLOGY ISSUES

There are a number of technology issues which should be addressed by NSF, or the proposed CSD Coordination Office, that are critical for many of the drilling initiatives proposed here. Many of these are specific to certain environments (e.g., high-temperatures in active magmatic systems) while others affect a range of drilling environments and project types. These include:

- *Down hole Observatories*. Permanent or semi-permanent downhole observatories for temperature, strain, or microearthquakes may provide a significant added bonus to many drilling projects. For many of these observatories, drilling the hole to place them into is often the most expensive part of the system. Installation of permanent or semi-permanent downhole observatories can be an extremely cost effective way to maximize the return on investment of drilling dollars.

- *Identify and develop robust sensor and deployment systems for long-term monitoring of strain, seismic waves, temperature, fluid pressure and fluid chemistry in active faults at temperatures of >120^{0}C and under chemically hostile conditions.*

- *Oriented Core for paleosecular variations and fabric studies*. Paleosecular variation in the Earth's magnetic field is a powerful tool for unraveling volcanic stratigraphy on a decadal or centennial time scale – far shorter than the uncertainties in Ar-Ar dates on young volcanic rocks. Without oriented core, only the inclination of remnant magnetism can be used. With oriented core, both the inclination and declination can be used, effectively doubling the resolving power of the technique.

- *High temperature down hole logging tools* (>150^{0}C) for slim hole projects (<15 cm diameter). Current tools max out at 70^{0}C or 140^{0}C, which is insufficient for studies of active magmatic systems, high-heat flow regimes, or geothermal settings.

- *Improved gas and fluid sampling tools* (down hole) for slim drill holes. Obtaining gas-saturated water samples from slim holes (<15 cm diameter) is a delicate operation that takes considerable rig time (e.g., 12 hours per run) and is often unsuccessful. Because water and gas chemistry is critical in many studies, more reliable tools are critical.

- *Develop or modify drilling/coring techniques, mud systems, directional control, downhole measurements and casing/cementation to maximize success in highly deformed and unstable fault zone environments.*

VII. SUMMARY AND RECOMMENDATIONS

Summary

Workshop participants discussed both the significant science issues addressed by a targeted program of continental scientific drilling of faults, fault zones, volcanoes, and volcanic terranes, and specific targets that can best answer these questions. The scientific questions and targets discussed here align with the priorities specified in the recent National Research Council report *"New Research Opportunities in the Earth Sciences"* (NRC, 2012), as well as previous NRC reports (NRC 2008, 2011).

Linkages with other Federal agencies (e.g., USGS, Department of Energy, Department of Defense), International Ocean Drilling Program (IODP), and international partners are critical to a successful U.S. scientific drilling program because resources can be leveraged across programs to maximize return on investment for all participants. Recent examples of intra-agency efforts include the Chesapeake Bay drilling project (USGS, ICDP), the Snake River Drilling project (DOE, ICDP, USAF), and the "PTA" drilling project on Mauna Kea (U.S. Army, NSF). Additional linkages should be sought with industries that rely on drilling (Oil-Gas, Geothermal).

Participants working on faults and fault zone processes highlighted two overarching topics: Understanding the seismic cycle (topic 1), and 4-dimensional mechanics and architecture of fault zones (topic 2). Five projects were recommended for consideration at this time, with several others recommended for consideration in the future after their concepts are more fully developed. The five recommended projects are:

1. *Reoccupying and extending the SAFOD site [white paper by Carpenter et al.]*
2. *Triggering earthquakes for science [white paper by Savage et al.]*
3. *Mechanics of the Sevier detachment [white paper by Christie-Blick et al.]*
4. *Tectonic evolution and mechanics of the Rio Grande rift [white paper by Ball et al.]*
5. *Fluid flow and supercritical fluid-rock interactions in the Little Grand Wash fault [white paper by Kampman et al.]*

The first two projects listed above address Topic 1 "Understanding the Seismic Cycle;" the next three projects focus on Topic 2: *"4-dimensional mechanics and architecture of fault zones"*. Other projects considered include two that focus on the San Andreas system, two that focus on extensional faulting in the basin and range, and one that examines linkages between faulting and volcanism in a pull-apart basin. Two projects (Rio Grande Rift and Mono Basin), are led by scientists from the USGS, and are part of larger efforts that have produced significant background data. Another (Dixie Valley) has linkages with DOE geothermal efforts.

Participants working on tectonics and magmatic activity defined three dominant themes: *Active Volcanism*, *Geodynamics/Chemical Evolution of the Earth*, and *Geoprisms*. In active volcanism, four projects were recommended for consideration at this time. The recommended projects are:

1. *Okmok Volcano, Alaska, USA [White Paper by Masterlink et al]*
2. *Aso Caldera, Japan [white paper by Nakada]*
3. *Mount St. Helens, Washington, USA*
4. *Newberry Volcanic Monument, Oregon, USA [White Paper by Frone]*

The first two projects listed above are backed by mature, well-developed proposals. The Okmok Volcano project is led by scientists from the USGS as part of their volcano hazards program. The Aso Caldera project, in Japan, would represent significant international effort, with much of the funding coming from international partners. Newberry volcano is the subject of current geothermal studies and has potential industry partners.

Participants working on Geodynamics and Geoprisms highlighted five projects for consideration at this time. The five recommended projects are:

1. *Deccan Traps, India: US Participation in the Indian Koyna Drilling Project and Joint ICDP-IODP Drilling of the Deccan-Reunion Hotspot track [White papers by Kale, Neal]*
2. *Snake River Plain Continental Plume Track [White Papers by Christiansen, Shervais, Hanan, Potter, Schmitt and Lee]*
3. *Mauna Kea PTA Project [White paper by Garcia]*
4. *Mauna Loa Project [White paper by Rhodes]*
5. *Drilling the Josephine Ophiolite – Direct Observation of a Subduction Zone Mantle Wedge [Shervais and Dick white paper].*

The Deccan project would focus on U.S. participation in a drilling project underway in India at this time, plus a IODP companion proposal to follow the hotspot lavas back to their place of origin. The Snake River and Mauna Kea projects have been already been drilled, or are in progress, with funding from the Departments of Energy and Defense; both represent opportunities to leverage intra-agency drilling funds to carry out important science investigations. The Mauna Loa project complements previous work on Mauna Kea, while the Josephine project addresses the geodynamics of subduction zones.

Broader Impacts

A primary goal of this workshop was to provide community input to NSF Program Managers that will assist them in setting programmatic goals and allocating resources. Another goal was to formulate a specific plan to apply continental scientific drilling to a range of significant and timely problems in faults, fault zone mechanics, active volcanism, and volcanic geodynamics.

Additional impacts will come through the workshop's cultivation of early career faculty, who will be the ones to initiate and carry out the research programs defined at the workshop. Involvement of early career faculty and, if possible, graduate students who are near completion of their PhD programs, will have an enormous impact on their future research success, as well as on the success of the continental scientific drilling program. They will also bring new ideas to the table that will impact current projects, and those already in process. The preparation and education of the geoscience workforce has a high priority in industry and academia, and the implementation of strong scientific drilling projects will enhance these goals.

"Addressing these and other earth science issues requires a well-educated and trained workforce. The Bureau of Labor Statistics projects that job growth will increase by 21 percent for geoscientists (geologists and geophysicists) and by 18 percent for hydrologists from 2010 to 2020, compared to 14 percent for all occupations. Despite high projected demand for earth scientists, however, the number of graduates in earth science fields has not fully recovered from a sharp decline in the early 1980s…" (NRC, 2013).

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Table 2. List of Presentations at Active Tectonic Workshop, by Themes (not order of presentation)

Presenter name	Other authors	Title
General Drilling presentations		
John Shervais		The CSD Proposal Process
Madelaine Lee	D. Schmitt	Borehole Geophysics - Applications and Limitations in Extreme Environments
Kerstin Lehnert		Data Informatics
Dennis Neilson		Drilling Technology: Review of tools, techniques, challenges
Faults		
Keynotes		
Jim Evans		Fault Rock Characterization
Virginia Toy		Fault mechanics in active systems
Jamie Kirkpatrick		Rapid response drilling
10 minute presentations		
Lyndsay Ball	J. Caine, T. Grauch, C. Ruleman	Evolution of Fault Zone Geology in an Active Continental Rift: Scientific Drilling Opportunities along the Sangre de Cristo Fault System, Northern Rio Grande Rift, Colorado
Brett Carpenter	J. Chester, S. Hickman	Capturing the Seismic Cycle: Sampling and Instrumenting an Earthquake Nucleation Patch at SAFOD
Nicholas Christie-Blick	M. Anders, G. Manatschal, B. Wernicke	Testing the Extensional Detachment Paradigm: A Borehole Observatory in the Sevier Desert Basin, Western United States
Jafar Hadizadeh	Thibault Candela, Joseph C. White, Francois Renard	Coring and studying clay gouges from mature active fault zones
Vivek Kale		Koyna - Warna Seismic Zone, Western India : A unique intraplate setting for drilling for an active fault zone underlying a basaltic pile
Niko Kampman	M. Bickle, J. Evans, D. Condon, C. Ballentine, G. Holland, Z. Zhou, Z. Shipton, M. Schaller, C. Rochelle , J. Harrington	Geological CO2 storage: constraints from scientific drilling of natural CO2 reservoirs, leaky faults and travertine deposits of the Colorado Plateau
Stephen Martel		Mechanics of Normal Fault Systems
Elizabeth Miller and Jeff Lee		Societal and economic importance of normal faults
Kentaro Omura		Drilling Investigations on the Mechanics of Faults; Downhole measurements to detect time variation of in-situ stress (20 Years after Fault Drilling)
Linda Reinen and Virginia Toy		The Puysegur Subduction Zone: Investigating the complex role of peridotite and serpentinite in the seismicity of the subduction zone interface
Heather Savage	N. van der Elst, J. Kirkpatrick	Earthquake Triggering and Fault Zone Drilling

Table 2. List of Presentations at Active Tectonic Workshop, by Themes (not order of presentation)

5 minute presentations:		
Patrick Fulton	E. Brodsky, Y.Kano, J. Mori, M. Kyo, F. Chester, Y. Namba, H. Muraki, N. Eguchi, S. Toczko, Y. Ito, T. Kasaya	The JFAST Observatory: Monitoring the frictional heat from the 2011 Tohoku Earthquake
Wade Johnson		A Brief overview of SAFOD Round 4 core solicitation
Liberty Lee		Active fault/volcanic terrane imaging borehole measurements for slip rates, physical property measurements, and improved surface imaging
Anja Schleicher	B. van der Pluijm	Clay growth in active fault zones
Ramesh Singh		Deep Drilling to Understand Tectonic Settings of Intraplate Earthquakes in US
Volcano Keynotes		
Keynotes		
John Eichelberger		Thoughts on the future of research drilling in volcanic systems
Michael Garcia		Mantle Plumes in Oceanic Crust: Insights from Deep Drilling
Clive Neal		Large Igneous Provinces (LIPs) and the IODP Connection
John Shervais	B. Hanan	Hotspots, Plumes, and Continental Lithosphere
10 minute presentations		
Michael Garcia	D. DePaolo, E. Haskins, N. Lautze, J. M. Rhodes, and D. Thomas	Detailed Probing of the Hawaiian Hotspot via New Drilling of Mauna Kea Volcano
Barry Hanan		Radiogenic isotope models for Snake River Plain basalt mantle source
Angela Jayko		Do Mono Basin and Long Valley overlie an incipient mantle plume? Or, are the late Holocene melts localized by transtensive block rotation within a regional releasing bend within the Walker Lane?
Tim Masterlark	W. Roggenthen, J. Eichelberger, J. Freymueller, P. Izbekov, and J. Larsen , M. Haney, C. Neal, S. Nakada, C. Thurber	Sampling and in-situ observations of Okmok
Michael Rhodes	F. Trusdell	Mauna Loa: Drilling the Other Side of the Hawaiian Plume
Loyc Vanderkluysen		Emplacement of large igneous provinces
5 minute presentations:		
Amanda Clarke		San Francisco Volcanic Field (or similar monogenetic basalt fields)
Zachary Frone		Newberry Volcano
Setsuya Nakada		Beyond Unzen and Campi Flegrei
Katherine Potter		an investigation of the kimama drill core: A Multi-Log Approach
Phil Wannamaker	J. Faulds, B.M. Kennedy	Magmatic-Hydrothermal Transitions in Extensional Geothermal Systems:A Deep High-Enthalpy Resource to Test with Drilling

Table 3 – List of White Papers at http://digitalcommons.usu.edu/geology_facpub/386/

Evolution Of Fault Zone Geology In An Active Continental Rift: Scientific Drilling Opportunities Along The Sangre De Cristo Fault System, Northern Rio Grande Rift, Colorado.	L.B. Ball, J.S. Caine, V.J.S. Grauch, C.A. Ruleman,
Capturing The Seismic Cycle: Sampling And Instrumenting An Earthquake Nucleation Patch	B. Carpenter, J. Chester, and S. Hickman
Reconstructing An "A-Type" Silicic Magma System Along The Track Of The Yellowstone Hotspot, Central Snake River Plain, Idaho	E.H. Christiansen & The Hotspot Science Team
Testing The Extensional Detachment Paradigm: A Borehole Observatory In The Sevier Desert Basin	N. Christie-Blick, M.H. Anders, G. Manatschal, And B. P. Wernicke
Understanding The Evolution Of A Back-Arc Bimodal Shield Volcano, Newberry Volcano, Oregon	Z. Frone
Volcano Structure And Hawaiian Plume Heterogeneity Based On New Drilling Of Mauna Kea	M. Garcia, D. Depaolo, E. Haskins, N. Lautze, J. M. Rhodes And D. Thomas
Coring And Studying Clay Gouges From Mature Active Fault Zones	J. Hadizadeh, T. Candela, J.C. White, F. Renard
Isotope Geochemistry And Mantle Source Regions For Plume-Lithosphere Interaction	B. B. Hanan
A Proposal To Drill Active Faults And Magmatism In A Major Intracontinental Fault Zone, Mono Lake Basin, Walker Lane, Western Great Basin, USA	A.S. Jayko And S. Martel
Koyna – Warna Seismic Zone, Western India : An Unique Intraplate Setting For Drilling For An Active Fault Zone Underlying A Basaltic Pile	Vivek S. Kale
Geological CO2 Storage: Constraints From Scientific Drilling Of Natural CO2 Reservoirs, Leaky Faults And Travertine Deposits Of The Colorado Plateau	N. Kampman, M. Bickle, J. Evans, D. Condon, C. Ballentine, G. Holland, Z. Zhou, Z. Shipton, M. Schaller, C. Rochelle & J. Harrington
Enhancing Data Management For Continental Scientific Drilling	K. Lehnert, A. Noren,
Mechanics Of Normal Fault Systems	S. J. Martel
Sampling And In-Situ Observations Of Okmok (SINOOK)	T. Masterlark, J. Eichelberger, J. Freymueller, M. Haney, S. Hurwitz, P. Izbekov, J. Larsen, S. Nakada, C. Neal, W. Roggenthen, C. Thurber
White Paper: Study Of The Thermo-Mechanical Aspects Of Extensional Fault Systems By Shallow Continental Scientific Drilling Into Paleo Brittle-Ductile Transition Zones And Top Of Channel Flow In The Basin And Range Province, Usa	E. Miller, And J. Lee
Large Igneous Provinces (Lips) And The IODP Connection	C. R. Neal
Drilling Investigations On The Mechanics Of Faults; Downhole Measurements To Detect Time Variation Of In-Situ Stress	K. Omura
Project Hotspot: Investigating Subsurface Basalt Using Wireline Logs	K. Potter
Proposal To Drill Into The Puysegur Subduction Zone: Investigating The Complex Role Of Peridotite And Serpentinite In The Seismicity Of The Subduction Zone Interface	L. A. Reinen1, V. G. Toy
Mauna Loa: Drilling The Other Side Of The Hawaiian Plume	J. M. Rhodes, F A. Trusdell, & M. O. Garcia
Earthquake Triggering And Fault Zone Drilling	H. Savage, N. Van Der Elst, & J. Kirkpatrick
Borehole Geophysics - Applications And Limitations In Extreme Environments	D. R. Schmitt & M.D. Lee
White Paper: Drilling The Josephine Ophiolite – Direct Observation Of A Subduction Zone Mantle Wedge	J. W. Shervais And H.J.B. Dick,
Tracking The Yellowstone Hotspot Through Space And Time	J.W. Shervais, B.B. Hanan, E.H. Christiansen, S.R. Schmitt & The Hotspot Science Team
Alpine Fault – Deep Fault Drilling Project (DFDP), New Zealand: Current And Future Opportunities For Active US Participation In An International Continental Fault Zone Drilling Project	V.G. Toy, J. Townend, R. Sutherland
Magmatic-Hydrothermal Transitions In Active Extensional Regimes Of The Western U.S.: The Need For Drilling To Assess Physico-Chemical State	P. Wannamaker